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Blackwater and Graywater on US Navy Ships: Technical Challenges and Solutions

ABSTRACT

Currently, the shipboard discharge of sewage within United States coastal waters is restricted by the Federal Water Pollution Control Act and specified in the Code of Federal regulations. Therefore, most US Navy ships are equipped with a Type III marine sanitation device (zero discharge) to collect and hold sewage generated in a twelve hour period during transit (0 to 3 miles), and to collect and transfer sewage and graywater to shore facilities when pierside. Future restrictions for sewage will be controlled internationally by the more restrictive MARPOL Protocol (Annex IV) standards. Graywater is not currently regulated, except in the Great Lakes and by some states. In the 21st Century, the discharge of graywater by military vessels in coastal waters will be controlled by the emerging Uniform National Discharge Standards (UNDS) legislation enacted in Sec. 325 of FY96 Defense Authorization Act.

In anticipation of more stringent environmental regulations, the increasing costs of waste disposal, and the need for naval combatants to operate unimpeded in littoral waters, the US Navy has identified the need to develop technologies which are appropriate for the control and treatment of blackwater and graywater. This paper will describe the status of development efforts by the Carderock Division, Naval Surface Warfare Center (CDNSWC) and its supporting contractors, under sponsorship of Naval Sea Systems Command (NAVSEA) and the Office of Naval Research. The challenge was to develop treatment systems that meet Navy shipboard requirements for affordability, compactness, low manning/maintenance, high reliability and safety, and EMI, noise, vibration and shock. Membrane ultrafiltration based systems, incorporating aerobic biological pre-treatment and ultraviolet light post treatment disinfection, have been developed to meet these requirements. Both external and in-tank membrane systems will be described in terms of performance, system operation and space and weight advantages.

INTRODUCTION

U.S. Navy ships generate significant quantities of blackwater (sewage) and graywater, up to 350,000 gal/day for an aircraft carrier. Graywater is the product of hotel and commissary-type activities aboard ships. Common sources of graywater are showers, sinks, laundry and galley and scullery equipment.

U.S. Navy ships are required to hold and not discharge blackwater in regulated areas throughout the world. This includes coastal areas within 3 mi. of the coast. Holding times vary from ship class to ship class, but generally amount to about 12 hours. The exception to this is DD-963 Class, which are able to burn and destroy blackwater onboard using vortex incinerators. Graywater discharge currently is not regulated except in the Great Lakes, but regulation is anticipated. However, current practice on many Navy ships is to avoid the overboard discharge of graywater in port when required. Because of this problem, costly upgrades to tankage on some US Navy amphibious ships are being implemented to increase wastewater holding times up to 36 hours (LHA ship class to hold 36 hours for combined graywater/blackwater, LPD-17 to hold 12 hours graywater, 36 hours blackwater). The cost of off loading blackwater (and graywater) while in port is expensive and costs are increasing worldwide.

Conventional biological wastewater treatment plants rely on large aeration tanks with settling/clarification chambers and long (> 20 hours) hydraulic retention times (HRT) to remove suspended solids and oxidize dissolved organic material. These systems require frequent attention, such as sludge wasting and periodic chemical additions (e.g. chlorine), and are space intensive. As a result, conventional biological systems are not particularly well suited for shipboard applications where space is a premium and manning is limited and being continually reduced. Short-term aerobic biological pre-treatment, however, emerged as an attractive concept when combined with membrane ultrafiltration systems being developed by the US Navy. Membranes effectively reject a high percentage of suspended solids and bacteria, and the bio conditioning would be expected to stimulate microbial activity that will consume the majority of the soluble organic content in the wastewater. If these systems can be designed to operate effectively at rather short residence times (<10 hours), they offer significant potential for shipboard non-oily waste treatment applications. This paper describes US Navy research and development efforts to demonstrate and validate the combined bio-conditioning and membrane filtration concept, using both in-tank and external ultrafiltration membranes.

BACKGROUND

Numerous conventional blackwater-graywater treatment processes have been evaluated by the Naval Sea Systems Command for their ability to meet Coast Guard Type II Marine Sanitation Device (MSD) effluent quality requirements as well as the operating requirements of naval combatants. However, most of these processes were determined not to be capable of Type II MSD effluent quality requirements or suitable for naval shipboard use. The confined space available to install, operate, and maintain these conventional treatment systems; low manning available for maintenance; and safety issues related to the storage and use of caustic, corrosive, and flammable chemicals required by the treatment processes make them unsuitable for naval shipboard use.

Blackwater and graywater are a high strength waste streams (Biochemical Oxygen Demand: 700-2500 mg/L and Total Suspended Solids: 300-1300 mg/L) composed of organic and inorganic particles and dissolved organic matter (starches, proteins, carbohydrates). Conventional filtration processes (media bed, strainers) are capable of removing the suspended matter to MSD Type II levels, but require frequent backwashing or filter media replacement. In addition, the large majority of methods capable of removing fecal coliform bacteria rely on biologically toxic chemicals which results in safety concerns for both the sailor and the aquatic organisms found in the receiving water body.

LEGISLATION AND LAWS

The U.S. EPA Clean Water Act of 1977[1] prohibited the discharge of untreated sewage in restricted navigable waters. No segregated graywater holding capacity was required for U.S. Navy ships with the exception of operations within the Great Lakes. However, several foreign countries and U.S. states including California, Washington, Virginia, Florida and Hawaii have begun to enforce more stringent water quality discharge standards that prohibits the discharge of graywater into navigable waters under their jurisdiction. In order to consolidate numerous and often varying local requirements, the Uniform National Discharge Standards (UNDS)[2] process is setting national standards for discharges from Vessels of the Armed Forces. In anticipation of UNDS and the tightened global wastewater discharge regulations outlined by MARPOL (International Maritime Convention for the Prevention of Pollution from Ships), the Chief of Naval Operations and Naval Sea Systems Command have identified the need to develop technologies that are appropriate for the control and treatment of combined shipboard graywater and blackwater (non-oily wastewater) as one of their environmental priorities.

TECHNICAL CHALLENGES

The combination of performance goals (throughput and high quality effluent) and the many constraints imposed by the US Navy shipboard environment results in a challenging engineering problem with a large number of trade-offs and life-cycle cost analyses that must be conducted. Some of the design constraints of the US Navy shipboard environment include: confined space available to install, operate, and maintain treatment systems; short deck-to-deck height; high strength waste; widely variable waste in-flow rates; extended periods of no flow; high degree of automation required due to limited or no manning available for operation and maintenance; shock, vibration, electromagnetic interference requirements, and safety issues related to the storage and use of caustic, corrosive, and flammable chemicals.

One example of a trade-off that must be conducted for a non-oily waste treatment system involves the limited space available to collect, hold and treat the waste. On one extreme, a system could collect and treat the wastewater continuously over a 24-hr period, and on the other extreme the system could provide minimal holding capacity and treat the waste as it is generated, up to the peak flow rate. The former case results in the smallest possible treatment system and the largest possible holding tank; the latter case is the opposite scenario. Therefore to determine the optimum combination of collection and holding tank size versus treatment system size, the design engineer will analyze a number of variables concurrently. The analysis for this example would consider the impact on treatment system performance (throughput and effluent quality) as well as the life-cycle cost of: continuous operation vs. intermittently operation; the ability of the chosen treatment process to manage rapid changes in waste characteristics as a result of minimal holdup volume and mixing; and the time required to repair equipment vs. the available tank volume to collect waste while conducting repairs.

The first step in solving the problem was a worldwide survey of industry for technologies suitable for the shipboard graywater and blackwater treatment conducted by CDNSWC. The technologies were evaluated in part based upon their relative performance in key areas including: ability to meet anticipated effluent limits; modularity; level of process complexity; volume/area requirements; ability of the process to respond to changing conditions or upsets; and availability of performance documentation to illustrate process maturity. Two technologies were identified as appropriate for subsequent laboratory evaluations and development: membrane filtration and evaporation. The evaporative process was subsequently evaluated in the laboratory with graywater. Results showed that the system could not reliably meet effluent quality standards and in addition was far too large for naval shipboard use. Membrane ultrafiltration and membrane filtration combined with aerobic conditioning of the waste was subsequently evaluated; the latter is under development.

MEMBRANE TECHNOLOGY

Membranes provide a straightforward and relatively simple means to separate and concentrate waste streams (up to 98%), and thereby decrease waste volumes and provide the opportunity to substantially increase holding times. Additionally, membrane systems require less space and power than phase-change process such as vaporization, are relatively inexpensive, and have many components in common with other shipboard mechanical systems. The U.S. Navy has previously evaluated membrane concentration of naval wastewater. In 1977, researchers found that ultrafiltration was an effective process for treating raw blackwater and activated sludge wastes, and for producing an effluent that met Federal discharge standards for total suspended solids and fecal coliform. These evaluations reported, however, that the membrane materials evaluated (mostly cellulosic) were not hardy and suffered rips and leaks. They also were not rigorous enough to withstand harsh cleaning procedures required to restore their performance. New membrane materials and manufacturing techniques, however, have been developed during the intervening 15 years, which has justified re-examination of membrane technology.

Membranes are thin barriers or films of material that allow certain substances to pass while rejecting others. Membranes that allow only some substances to pass through them are called *semipermeable membranes*. Most commercially available membranes are made from polymers, ceramics, metals, or porous materials impregnated with liquid or gelatin-like substances. The pore size and distribution of the membrane material is designed to allow certain sizes of molecules, ions, and particles to pass and are classified accordingly. Membrane throughput or flux is controlled by the driving force (positive or negative pressure) and reduced by the fouling rate. As with conventional filtration systems, membranes typically operate at room temperature.

MEMBRANE – BIOREACTOR CONCEPT

Membrane-bioreactors (MBR) combine membrane separation with biological treatment into a single process. In the MBR process, membranes are used to separate biological and inorganic solids from the treated water. This process is different from the application of membranes that are used downstream of biological processes for polishing purposes. The MBR process is similar to the conventional activated sludge treatment process wherein raw wastewater enters the bioreactor and mixes with suspended biological solids containing microorganisms. The microorganisms degrade the dissolved organic matter and convert it to cellular matter and carbon dioxide, which is vented from the system as a gas. Any excess biological solids are removed from the bioreactor on a regular basis in order to maintain a desired concentration of suspended solids. The membrane filters are used to separate the biological solids from the raw graywater. These solids are then returned to the bioreactor. The treated effluent may be discharged or sent to additional treatment processes depending upon discharge requirements. The MBR process is also readily adapted for nitrification and denitrification in much the same way as conventional activated sludge.

Compared to conventional activated sludge processes, MBRs by design produce less sludge due to the long sludge age (>30-days) typically used. The long sludge age, however, would adversely impact the sludge settling unit operation in conventional biological treatment processes. An important feature of MBRs is the low volume to area requirement that is possible as a result of the high concentration of suspended biological solids, which is possible due to the membrane separation process. The high concentration of suspended solids is not possible with conventional gravity settling and the high concentration of biological solids allows for a higher efficiency of waste treatment per unit volume of process tank.

SYSTEM DEVELOPMENT AND DEMONSTRATIONS

Evaluation of a Pilot Scale Commercial System

In response to a competitive solicitation, a pilot-scale laboratory membrane-bioreactor filtration system was designed and built by a US wastewater treatment manufacturer in an attempt to meet secondary wastewater discharge standards of five day biochemical oxygen demand (BOD_5) of less than 30 mg/L, total suspended solids (TSS) less than 30 mg/L, and fecal coliform (FC) count less than 14 counts per 100 ml of sample. The system produced for CDNSWC in February 1993 consisted of a skid mounted assembly with a three chambered biological waste treatment tank with internal air diffusers, a tubular (25mm diameter) ultrafiltration membrane filtration system, a granular activated carbon adsorber, and an effluent ultraviolet light disinfection system. The entire system was designed to have a minimum hydraulic retention time (HRT) of 24 hours. The system was tested using graywater from the US Naval Academy scullery/galley and laundry operations.

The system performance testing was conducted in the laboratory early in 1993 for approximately 650 hours and was successful in meeting the effluent water quality criteria. The system, however, was large (4900 liters) for a 3.8L/minute system and required a HRT greater than desired. Also, it was found that there was a need to pre-screen or pre-settle the feed to eliminate clogging of the membrane recirculation pump.

Bench Scale Research Studies

Based upon positive results from the pilot-scale laboratory membrane-bioreactor filtration system, the Office of Naval Research sponsored a bench scale research program at Purdue University to investigate the range of conditions under which a membrane-bioreactor system would satisfactorily operate. Purdue researchers studied the chemistry of typical shipboard generated graywater; the structure, function, and biodegrative potential of the bioreactor microbial communities; and the response of the aerobic microbial communities to perturbations and system "shocks". The overall goal of this research was to verify the use of the bioreactor to rapidly and reliably treat graywater. Using a bench-scale membrane-bioreactor and synthetic graywater, the Purdue researchers were able to demonstrate that the bioreactor could degrade the graywater rapidly (within several hours) and with stable operation[3]. Some key findings from this research program are as follows:

- The membrane-bioreactor was maintained at a hydraulic retention time (HRT) of 3 hours for 10 days with an acceptable BOD (30-ppm) in the membrane effluent.
- There is a linear increase in biomass with respect to time as the bioreactor is started. The biomass concentration plateaued at approximately 50-fold higher than that found in a continuous flow (no biomass recycle) biological reactor.
- Virtually all of the organic carbon that enters the reactor is completely oxidized by the microbial population to carbon dioxide; relatively little is used for biomass synthesis (sludge).
- The membrane-bioreactor was operated up to 74 days without significant build up of solids within the reactor.
- Environmental perturbations evaluated had only a short-term effect on bioreactor performance. The perturbations studied included: no aeration for 24 hours, stopping the flow of substrate inflow for 15 hours and the addition of a 2 vol. % hypochlorite solution[4].

Modified Pilot Scale Laboratory System

Encouraged by the positive results of the bench scale research conducted by Purdue University, CDNSWC decided to modify the pilot scale bioreactor-membrane filtration system in an attempt to validate these short time HRT results at a larger scale. System modifications took place in June 1995 and included removing the carbon filter and the ultraviolet disinfection system and replacing the tubular membranes with a submerged, in-tank, hollow fiber membrane module. The module is composed of 1.6-mm diameter membrane hollow fibers manufactured from a polymeric microfilter material outer skin with a molecular weight cut off 200,000. Permeate passes from the outer membrane wall and in through the lumen of the membrane. The membrane module is comprised of a bundle of hollow fiber membranes attached to a header on either end. Slotted PVC pipes are attached to the bottom of the membrane module to diffuse air on to the membrane. The diffused air scours the membrane surface to help maintain its productivity. A vacuum pump attached to the headers provides the necessary transmembrane pressure to ensure adequate permeate flow (i.e., flux).

This modified aerated system was then evaluated between November 1995 and April 1996 at two different hydraulic retention times, 18 and 6 hours, while treating graywater. The purpose of these tests was to evaluate whether biological treatment of graywater in conjunction with hollow fiber membrane separation could operate reliably and meet the effluent quality performance goals listed in Table 1. These tests also served as a pilot-scale validation test for the bench-scale research conducted by Purdue University.

Table 1. Effluent Water Quality Performance Goals for Graywater Treatment (Minimum of MARPOL Annex IV & US Coast Guard MSD Type II Standards)

Water Quality Parameter	Effluent Water Quality Goal
Biochemical Oxygen Demand (BOD_5)	≤ 50 mg/L
Total Suspended Solids (TSS)	≤ 100 mg/L
Fecal Coliform (FC)	≤ 200 colony forming units / 100 mL

The results of these tests are shown in Table 2 and reveal; that at the 18 and 6 hour HRT, the aerated membrane filtration system (AMTS) operated in a stable condition and successfully met the effluent quality goals. The system was tested using graywater from the US Naval Academy galley and laundry operations. System performance was assessed in terms of effluent water quality, membrane flux and biological characteristics. The membrane flux remained steady throughout the test period without chemical cleaning. The growth and stability of the microbial population were characterized by measuring the concentration of cell protein, total suspended solids (TSS), and total volatile solids (TVS) in the bioreactor. A robust microbial population developed in the tests evident by the magnitude and growth levels of cell protein, TSS, and TVS in the tank. This microbial activity resulted in reduced levels of BOD_5 in the permeate.

Table 2. Results of Laboratory Evaluation of In-Tank Membrane/Bioreactor System with Graywater

HRT (hours)	Average Flux at 20^0C (LMH)	Test Duration (hours)	Average BOD (mg/L)		Average TSS (mg/L)		Average Fecal Coliform (cfu/100 mL)	
			Feed	Permeate	Feed	Permeate.	Feed	Permeate
18	23	433	N/A	41	N/A	N/A	N/A	N/A
6	17	880	342	10	197	2	2.7 x E5	42
6	12	764	506	6	238	10	6.4 x E4	16
3	9	662	1426*	93	1278	7	6.6 x E6	490
		Shipboard Graywater**	845	-	345		4.2 x E7	-

N/A not available
* Carderock test with stronger graywater feed source
** USS L.Y. SPEAR

The pilot-scale treatment system performed successfully for over 400 hours in the 18-hour HRT test and 1800 hours in the six-hour HRT tests. Combined biological conditioning and membrane filtration of the graywater effectively removed soluble organics that typically pass through ultra, micro and even nanofiltration membranes. The system produced an effluent that met the performance goals listed in Table 1. The system also demonstrated the ability to achieve very high volume reductions (VR) by discharging the permeate and concentrating the membrane retentate. For example, a VR of 120:1 was achieved in one of the six-hour HRT tests. The significance, of course, of a high volume reduction is that for a given tankage allowance, a naval combatant could hold the concentrated wastewater for a much longer mission duration.

The success of the AMTS at treating graywater at an HRT of six hours prompted testing at an even lower HRT of 3 hours. Tests were conducted in the new Carderock Division Environmental Quality Laboratory located in West Bethesda, Maryland. An ultraviolet (UV) disinfection system was added to a new AMTS lab scale unit to aid in disinfection of the membrane permeate. The graywater used in this test was acquired from a commercial laundry service and a military galley facility. As Table 2 shows, the source graywater at the new Carderock facility was much stronger than that of the graywater acquired from the US Naval Academy. (BOD and TSS levels also were greater than shipboard generated graywater.) As a result, the performance of the treatment system, shown in Table 2, was not as successful as achieved with a weaker graywater feed at a 6 hour HRT. While the TSS goal of <100 mg/L was met, both the fecal coliform concentration and the BOD exceeded the effluent quality goals. The flux of this test was also much lower than that seen in the previous testing, presumably due to the stronger feed and longer usage period with the membranes.

Benchmark Pierside Testing

In the summer of 1996, an opportunity presented itself to conduct a benchmark evaluation of the AMTS concept pierside at Norfolk Naval Station. A temporary AMTS unit was fabricated consisting of a 1900 liter aerated bio-conditioning tank, three in-tank hollow fiber membrane modules and an UV post treatment disinfection system. The purpose of this pierside evaluation was to develop confidence in the AMTS process by treating actual shipboard generated wastewater in anticipated support of a contract design effort for a large scale pierside prototype (see following section).

During the benchmark testing, sewage and graywater were processed from ships configured with both gravity collection holding and transfer tanks (CHT) and with vacuum collection holding and transfer tanks (VCHT). The goals were to achieve a volume reduction of at least 50:1 while producing an effluent meeting the standards listed in Table 1.

Five separate system tests were conducted. Tests 1-4 were all conducted at a hydraulic retention time of 3 hours. During Test 5, the hydraulic retention time was increased to six hours. The results of these tests were generally positive as shown in Table 3. While the BOD effluent quality goal was not met in all tests, the TSS, and FC effluent quality goals were realized. In addition, the system performed in a stable manner, while concentrating the wastewater to high levels. For CHT ships, the 3-hour

HRT appeared to be adequate. For VCHT ships, more testing is required to determine a minimum HRT necessary to achieve the effluent water quality goals.

Table 3. Results of Pierside AMTS Benchmark Testing of Shipboard Generated Non-Oily Wastewater

	Test #1 (CHT)	Test #2 (VCHT)	Test #3 (VCHT)	Test #4 (CHT)	Test #5 (CHT)
HRT (hours)	3	3	3	3	6
BOD_5 (mg/L)					
Feed	1,268	1,445	1,423	980	274
UF Permeate	63	115	201	40	26
TSS (mg/L)					
Feed	759	590	778	811	201
UF Permeate	1	1	4	9	1
FC (CFU/100 mL)					
Feed	1.24E+08	8.66E+07	5.49E+06	1.21E+08	1.21E+08
UF Permeate	8334	7,450	590	278	1,672
UV Effluent	10	62	58	32	5
Average Throughput (L/min)	9.8	7.2	9.5	5.3	9.1
Volume Reduction	35	60	43	59	55
COD (mg/L)					
Feed	2120	2764	2339	2076	815
UF Permeate	176	273	395	228	297
TOC (mg/L)					
Feed	327	316	455	613	83
UF Permeate	47	62	130	76	20
TDS (mg/L)					
Feed	9504	810	884	5215	9494
UF Permeate	8606	518	538	4796	9522
TKN (mg/L)					
Feed	96	125	92	98	63
UF Permeate	35	61	68	24	42
O&G (mg/L)					
Feed	66	95	29	67	51
UF Permeate	1.1	2.0	1.3	3.0	2.2

BOD_5 - Five Day Biochemical Oxygen Demand
TSS - Total Suspended Solids
FC - Fecal Coliform
COD - Chemical Oxygen Demand
TOC - Total Organic Carbon
TDS - Total Dissolved Solids
TKN - Total Kjedahl nitrogen
O&G - Oils and Greases

AMTS Pierside Demo Project

Based on the successful benchmark testing, a shipboard scale (75-person) AMTS, with submerged in-tank hollow-fiber membrane modules, is being designed and will be fabricated and demonstrated pierside. This summer, a contract was awarded to a Canadian company to produce the transportable prototype AMTS which will process non-oily wastewater generated from naval ships equipped with graywater and vacuum blackwater collection. The project involves cost sharing by the Canadian vendor and the Canadian Government (Industry Canada). The US and Canadian Navies will collaborate during the design and development of the prototype. The system is intended to produce an effluent quality meeting combined IMO MARPOL Annex IV and US Coast Guard Marine Sanitation Device (MSD) Type II Standards listed in Table 1 and will provide at least a 15-day retentate holding capacity, concentrating the feed stream > 40:1. The AMTS prototype will be designed to fit in a 12m long mobile trailer to be tested pierside by CDNSWC personnel at the Norfolk Naval Station, Virginia. Details of the prototype design currently are being finalized. Fabrication of the unit will take place early in 1999. The transportable system will consist of a pierside equalization/collection tank and a treatment tank consisting of a bioreactor section, a membrane filtration section (containing several submerged hollow fiber modules) and a sludge retentate holding section. Conceptual arrangement drawings are shown in figure 1-3. It is expected that the prototype will be delivered to the US Navy in the spring of 1999. After contractor acceptance testing, the large scale AMTS will be evaluated for five months by CDNSWC to determine system performance, reliability and the ability to handle unanticipated "upsets" (toxic shocks). After completion of this testing, the Canadian Navy has expressed interest in evaluating this prototype unit pierside with Canadian warships in Halifax, Canada.

Figure 1: Isometric Component Schematic of Large Scale AMTS

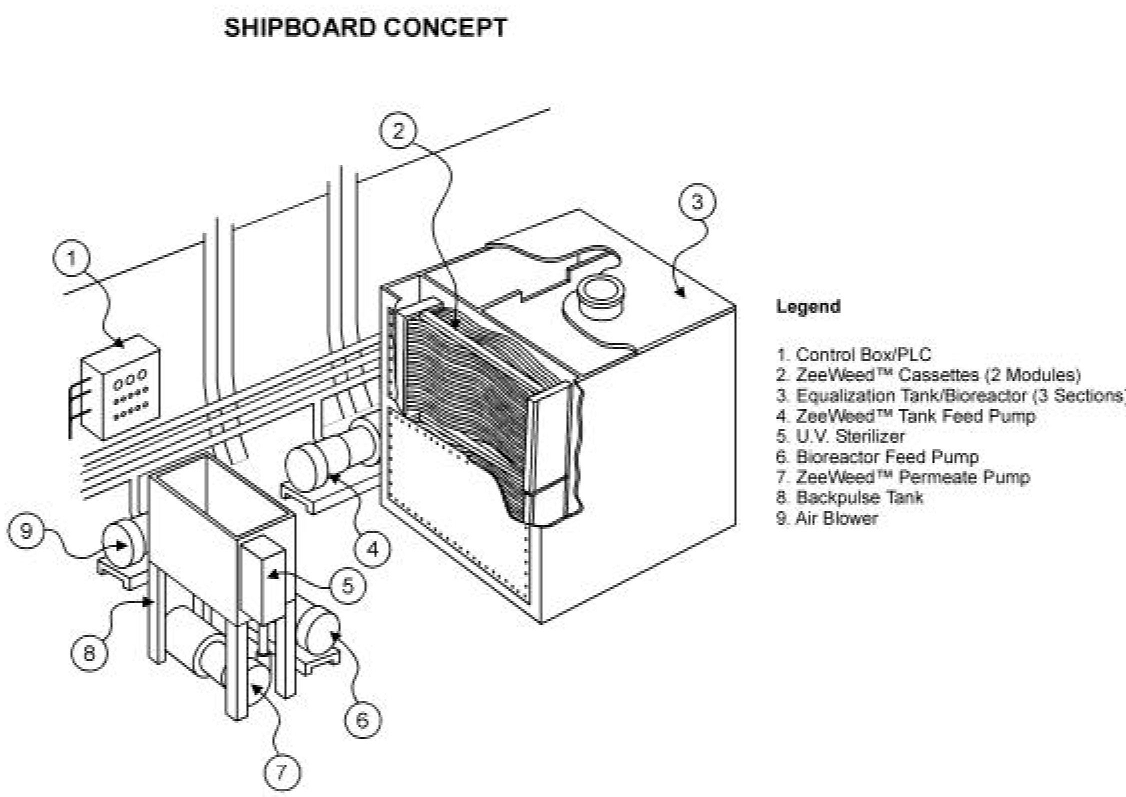


Figure 2: Isometric Flow Schematic of Large Scale AMTS

PIERSIDE DEMONSTRATION SYSTEM

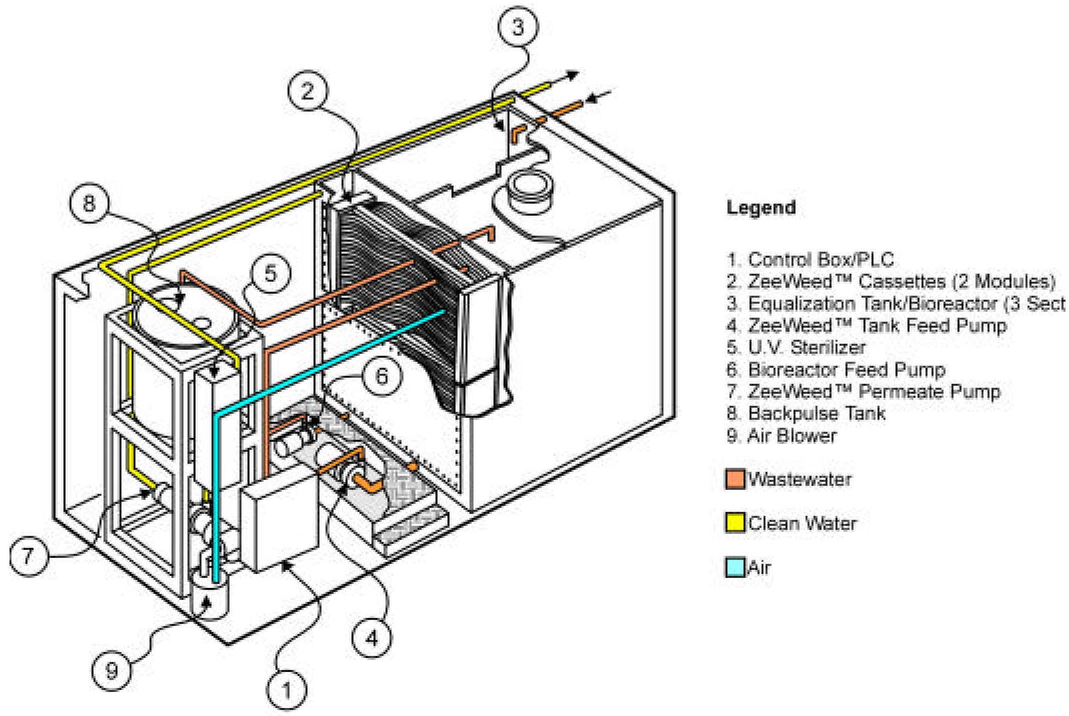
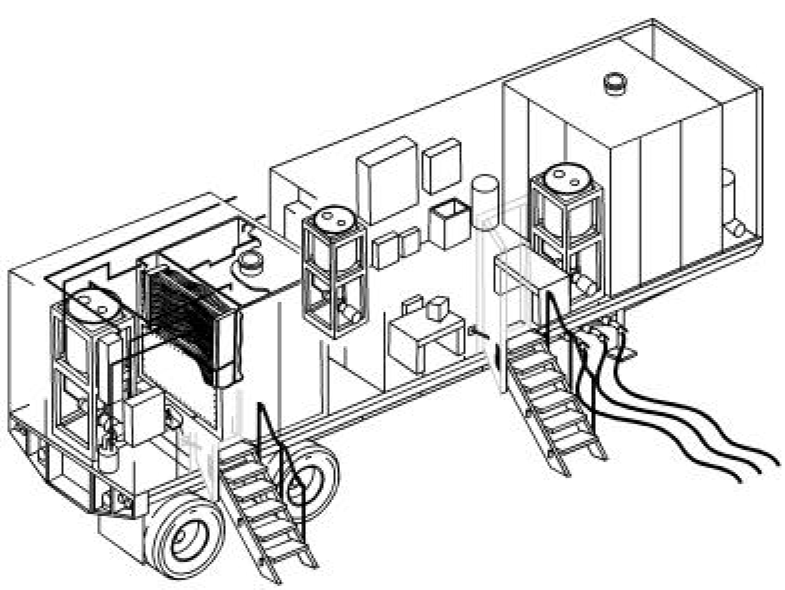


Figure 3: Isometric Schematic of Large Scale AMTS Trailer

PIERSIDE DEMONSTRATION SYSTEM



Engineering Development Model-1

Concurrently, a graywater treatment engineering development model (EDM) has been designed by a CDNSWC design team and is being fabricated for comprehensive laboratory evaluation prior to a shipboard demonstration under sponsorship of Naval Sea Systems Command (SEA 03R24). Unlike the AMTS prototype describe above, this system will employ an external (out-of-tank), skid-mounted, membrane filtration system consisting of large bore (~ 25mm diameter) bundled tubular membranes. Each bundled module consists of 8 tubes that are 2m long arranged in a heat exchanger configuration. The macerated and aerated feed stream will be biologically conditioned at a retention time of 8 hours and recirculated through the ultrafiltration tubes. The "clean" water will permeate through the walls of the membranes and the retentate will be held in the aeration holding tank. The permeate is pumped through an ultraviolet light reactor to ensure a sterile effluent prior to discharge. System throughput is approximately 10L/min. The system will concentrate the graywater 50:1. When eventually installed on a ship, the skid-mounted system will be nominally 2.5m long x 1.6m wide x 1.7m high with a "wet" weight of approximately 15000-kg (including the aeration holding tank). Comprehensive testing, evaluation and system optimization is underway at CDNSWC (see Figures 4-7).

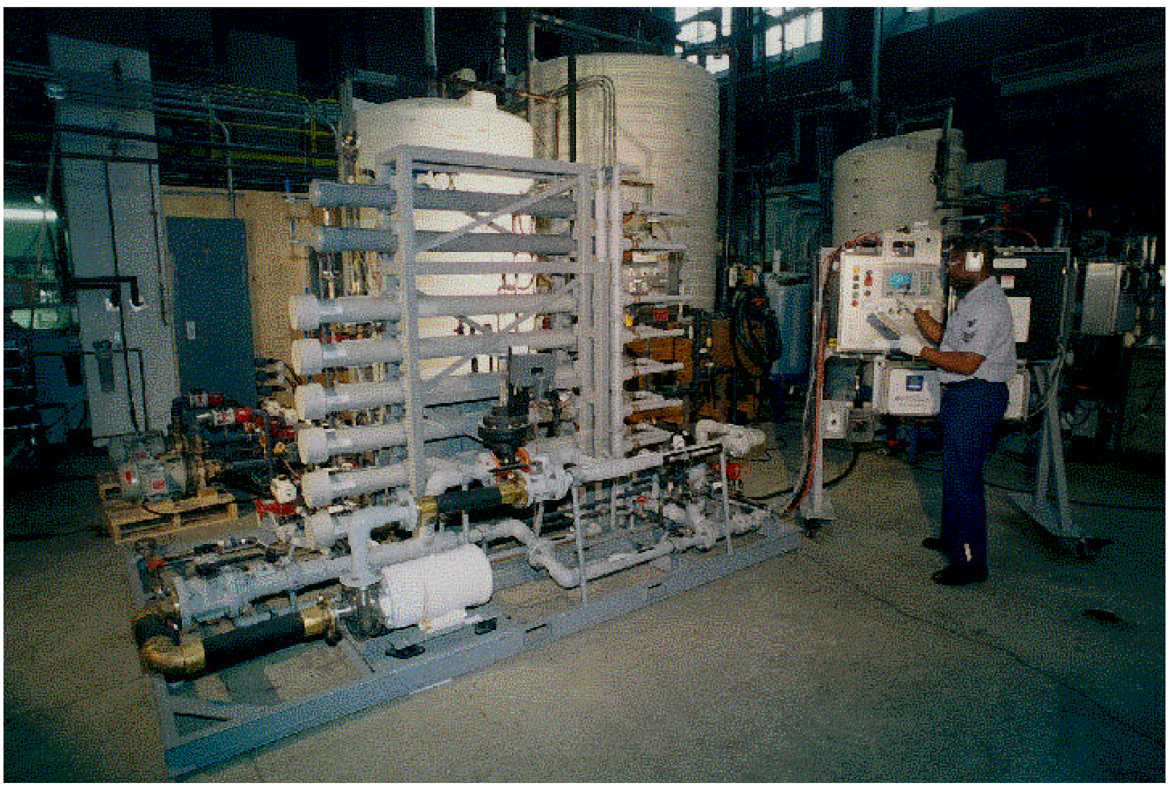


Figure 4. Laboratory Graywater EDM-1

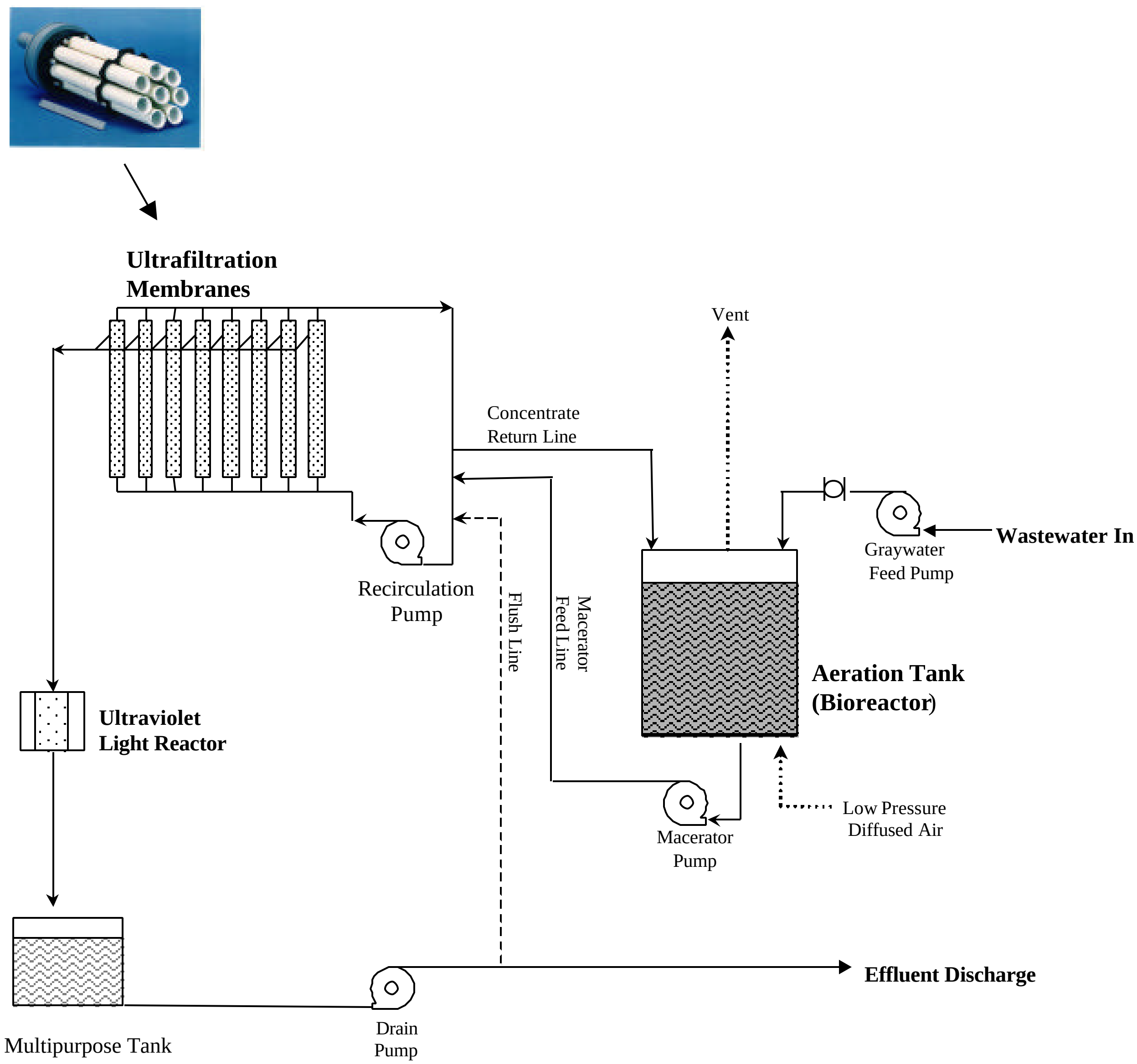


Figure 5. Simplified Laboratory Graywater EDM Process and Instrument Diagram

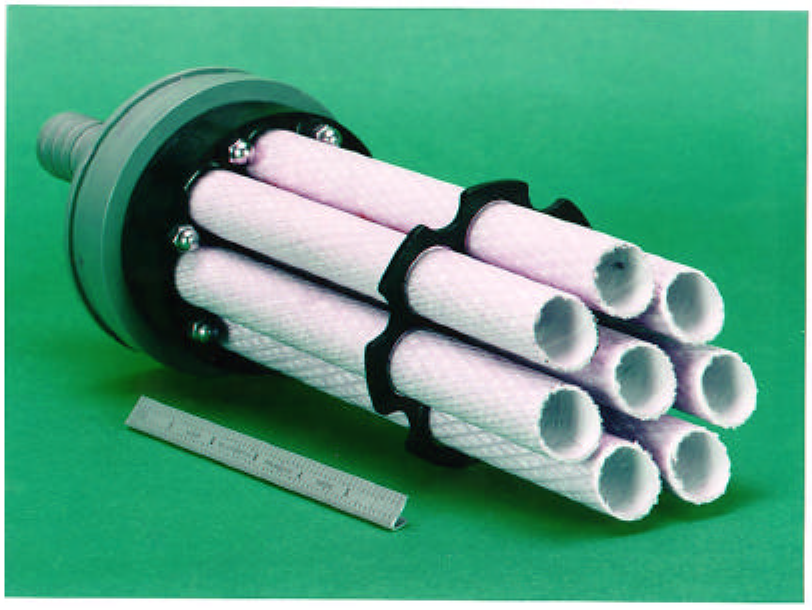


Figure 6. ZPF-8 Membrane Module with 0.83-inch diameter tubular membranes

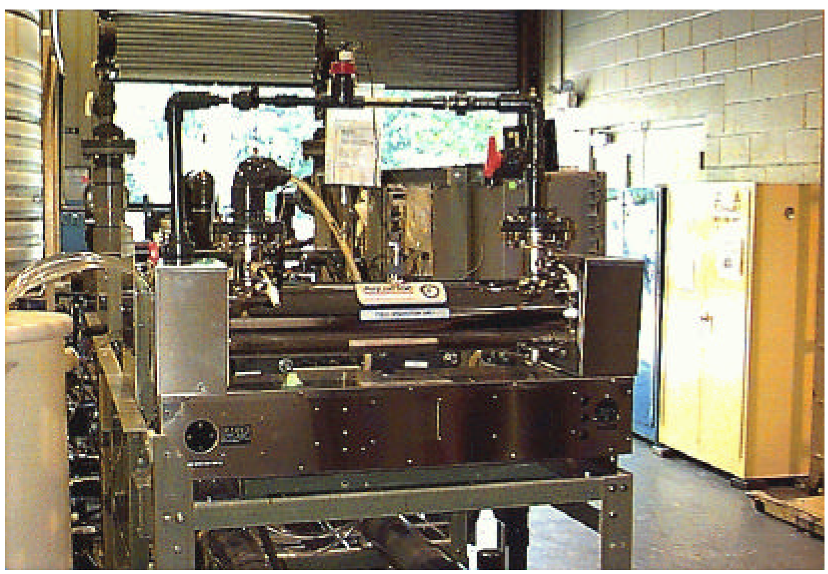


Figure 7. Aquafine CSL-4R, four bulb, UV disinfection unit (Model CSL-4R)

EDM-1 Laboratory Evaluation

Experimental Procedure

During the laboratory evaluation, EDM-1 operated automatically (unmanned) for 24 hours/day during which time graywater was processed approximately 15 hours/day at 2.5 gallons/minute. Roughly 2,500 gallons of raw graywater was processed daily. While processing, aerated graywater was pulled from the aerated holding tank (bioreactor) and concentrated in the membrane loop as permeate was continuously removed. Raw graywater was supplied to the bioreactor in a ratio of 1 part galley to 10 parts laundry wastewater. This ratio resulted in a graywater mixture with characteristics similar to shipboard graywater. This raw graywater was added to the bioreactor in a schedule representative of a U.S. Navy vessel's anticipated graywater generation rate (Figure 8).

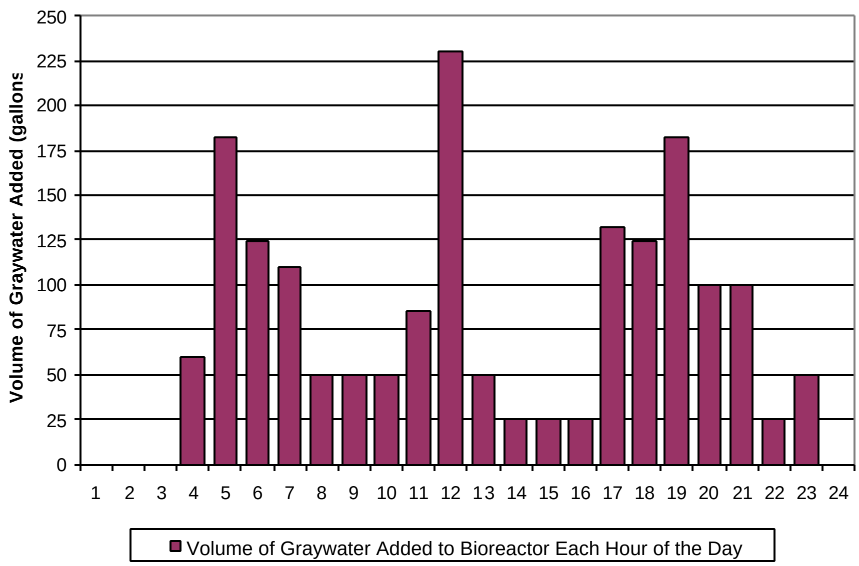


Figure 8: Daily Feed Schedule

Based on the graywater transfer and resulting treatment schedule, one tap water flush of the treatment system was expected a day, at approximately 2300 hours (11:00 PM) with an average flush temperature of 50°C.

Test Results

Two phases of the laboratory comprehensive laboratory evaluation have been completed. The objective of the laboratory evaluations are to operate the graywater treatment system under realistic shipboard scenarios and evaluate the system performance relative to design goals for throughput, effluent quality and reliability.

During phase 1 of the evaluation, the EDM-1 was operated for 37 consecutive days (600-hr). This test simulated more than a 30-day mission in which the ship remained independent of shore-side support. The system succeeded in meeting test objectives for: throughput (2.5 gal/min), effluent quality for total suspended solids and fecal coliform, reliability (no equipment failures), and retaining sludge for 30 days.

Although the system only met the biochemical oxygen demand effluent quality goal for two-thirds of the samples, the average and geometric mean values for the entire sample set met the goal of 50 mg/L. The samples that did not meet the effluent quality goal may have been as a result of inadequate bioreactor aeration at particular points throughout the test; acceptable BOD values were noted as early as the second test day which indicates a rapid start-up.

During phase 2 of the evaluation, the EDM-1 was operated for 40 consecutive days (430-hr) of which graywater was processed for 30-days. The system processed graywater 15-hr per day during the 5-day work week and remained idle (without graywater feed) during the weekend. This test simulated a series of consecutive short missions separated by short periods in port. In this test the treatment system must quickly alternate between no use and full use; a challenge for biological treatment systems. The system succeeded in meeting all test objectives: throughput (2.5 gal/min), effluent quality, reliability, and retaining sludge for 30 days.

A final evaluation of the EDM-1 system will be a six-month laboratory test during 1999 to determine whether the treatment system can achieve 180-days of consecutive operation without a critical failure, thereby meeting Navy goals for reduced manning and maintenance. The system will be operated in much the same manner as the previous test phases but sludge will be removed automatically from the system. The sludge wasting will begin between the 20th and 30th day of graywater processing depending on membrane permeate flow rate and continue for the duration of the test. The wasting process is required in order to maintain the necessary microorganism reactivity as well as the desired suspended solids concentration in the bioreactor to maximize membrane life.

TREATMENT SYSTEM COMPARISONS

The two membrane-bioreactor treatment systems described each have their own set of advantages and disadvantages that make them attractive for shipboard graywater and combined graywater-blackwater treatment. The AMTS, with its in-tank membrane has potential savings in space, weight, energy, and operational cost. The EDM system, with its external tubular membranes, provide for easy access and maintenance of the membranes without the need to drain and gas-free a wastewater tank. The large channel tubular membranes are also well suited to wastewater streams that contain high solids concentrations and fibrous material without prefiltration requirements.

During 1999, laboratory and pierside demonstrations combined with trade-off and ship impact studies will provide the data necessary to optimize the selection for future ship classes.

THE FUTURE

2008

It is envisioned that early in the 21st Century, the discharge of graywater in coastal waters and special areas will be regulated. The US Navy and the US EPA are currently working together to establish regulations that will govern graywater discharge under the Uniform National Discharge Standards legislation. In addition, the prohibition of the discharge of non-oily wastewater streams from naval and marine vessels may be extended from 3 mi. to 12 mi. from coastal regions. This will place a significant constraint on the cost, operation and mission duration of the Fleet in littoral waters. In addition, the ability to use chlorine treatment for disinfection will be discouraged or even prohibited. Shipboard wastewater membrane filtration systems will be required to address and alleviate these constraints.

2025

Stringent effluent water discharge requirements will be imposed worldwide. “Special areas” may be extended. Shipboard air pollution requirements may restrict the widespread application of thermal destruction methods (incineration) onboard US Navy ships. The cost of offloading any waste streams may be cost prohibitive. Reduced Fleet size may require longer ship deployments and, thus, longer hold times for wastewater. It will be necessary for the Fleet to be “environmentally self-sufficient”. The Environmentally Sound Ship concept will likely be a necessity.

SUMMARY

Laboratory and pierside prototype membrane-bioreactor treatment systems have been developed and are being tested while processing graywater and combined graywater-blackwater. These systems have been designed to meet the unique shipboard challenges and requirements demanded by future US Navy combatants. Both systems have been evaluated in the laboratory using Navy-generated land-based graywater mixtures and pierside at Norfolk Naval Base. Currently the graywater treatment system based upon tubular membrane filtration is undergoing advanced engineering development while a full-scale AMTS will be completing a technology demonstration at Norfolk Naval Base. Both systems are candidates for installation aboard 21st Century Naval combatants. The systems use polymeric membranes to trap coarse and fine solids and to remove a significant amount of biochemical oxygen demand (BOD) and fecal coliform bacteria. In order to avoid environmentally undesirable doses of chlorine, an enclosed ultraviolet light reactor is being used to ensure disinfection of the UF membrane effluent. Aerobic conditioning in conjunction with membrane filtration is being evaluated to ensure that all anticipated 21st Century effluent water quality goals will be met.

ENDNOTES

1. “Federal Water Pollution Control Act,” As Amended (33 U.S.C. 1251 et seq.)
2. Fiscal Year 1996 National Defense Authorization Act, Section 325.
3. Konopka, A., Zakharova, T., et. al. “Biodegradation of Organic Wastes Containing Surfactants in a Biomass Recycle Reactor”. Society of General Microbiology (U.K.) Abstracts, 1995.
4. Oliver, L, Zakharova, T., Konopka, A., et al. “Sodium Hypoclohrite Perturbation of a Graywater Treatment System. American Society for Microbiology; Abstracts of Annual Meeting, 1996.

ADMINSTRATIVE INFORMATION

The graywater treatment system development is sponsored by the Naval Sea Systems Command (NAVSEA). The research development program manager is Mr. Carl Adema (SEA 03R24). The Aerated Membrane Treatment System development is sponsored by the Office of Naval Research (ONR). The program officer is Mr. Kelvin Higa (ONR 331).

Description of Operation Parameters:

Flow rate = the volume of graywater processed over time. Assuming that a ship creates on average 30 gallons graywater per sailor per day, and that graywater is being generated for 17 hours of those hours, a graywater treatment system serving 75 sailors needs to process 2.5 gallons graywater/ minute. If the graywater treatment system cannot maintain this rate the system would overflow.

Permeability = the flow rate normalized to a common temperature and pressure (20^{o}C, 1 bar). The permeability shows the relative ease with which permeate passes through the membranes (while the system maintains a constant programmed permeate flow rate). A slow decrease in permeability over time is usually indicative of membrane fouling (either particulate or biological, which can build on the surface and/or in the pores). A sudden decrease in membrane permeability may indicate a blockage.

TMP = "Transmembrane Pressure", as determined by the average pressure across the membrane surface (tube to shell)[1]. Not only does the TMP demonstrate the pressure drop through the membranes, but is also provides a safety parameter for the fairly fragile membranes. The polymer membranes used in the EDM-1 system should not have a TMP higher than 45 psi[2] as a higher pressure can cause rupture.

Description of Treatment Parameters:

BOD = "Biological Oxygen Demand". The BOD is a measure of how much organic matter is available as food in the graywater. A low BOD (< 50 mg/L) is desirable in overboard effluent since algae blooms and other prokaryote outbreaks occur when high nutrient levels are available. In most wastewater testing, the BOD is analyzed over a five-day period and is reported as BOD_5. A bioreactor is critical in reducing BOD in the EDM system as the bacterial population digests the organics initially present in the graywater.

TSS = "Total Suspended Solids". The TSS is a measure of the amount of suspended solids, both organic and inorganic, found in wastewater. A suspended solids level below 100 mg/L is desirable in overboard effluent.

FC = "Fecal Coliform". Fecal Coliform (FC) is a common bacterium found in wastewater that can cause gastric disease in humans. Levels of fecal coliform are measured in "colony forming units", cfu (essentially a bacterium capable of reproducing), per milliliter of wastewater. Overboard effluent should have less than 200 cfu/ml.

Oils and Greases (O/G) = the amount of oils and greases found in graywater. There are no regulatory limits on the amount of oils and greases present in the effluent, but it has been surmised in the laboratory that high O/G levels in the bioreactor prevent the bacterial from effectively reducing BOD.

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[1] Note: in some tests the TMP is referred to as the THP (transheader pressure) because the pressure transducers were mounted on the membrane headers, not on the membranes themselves.
[2] Based upon an assumed maximum safety inlet pressure of 65 psi and the system's piping configuration.

Definitions

Concentrate: The portion of the feed solution that does not pass through the membrane, but is retained within the processing loop of the EDM system (retentate).

Daily Clean Water Flush: The systems are flushed at the end of each test day with 50°C tap water to clean all concentrate off the surface of the membranes.

Hydraulic Retention Time: The average amount of time a theoretical graywater molecule is retained in the system before exiting [overboard] as effluent.

Membrane Flux: Liters of permeate produced per square meter of membrane per hour, normalized to 20°C.

Operational Run Time: The cumulative time the EDM system is powered and available to process graywater (clock time).

Permeability: Liters of permeate produced per square meter of membrane per hour, normalized to specific temperature and pressure (20°C, 1 bar). This parameter, designated Q_{20}, is an indicator of membrane fouling.

Permeate: The portion of the feed solution that passes through the membrane.

Processing Time: The time EDM is actually processing graywater.

Transheader Pressure: Transmembrane pressure as measured off the membrane headers vs. the membranes themselves.

Transmembrane Pressure: The effective pressure at the membrane surface as calculated by:

$$\left(\begin{array}{c}\text{Trans. Mem.}\\ \text{Pressure}\end{array}\right) = \frac{\text{Inlet Pressure} + \text{Outlet Pressure}}{2} - \left(\begin{array}{c}\text{Permeate}\\ \text{Pressure}\end{array}\right)$$

Volume Reduction: 20:1 volume reduction means that of 20 gallons of feed water processed, one gallon of concentrate remains.

Abbreviations

‘	Feet
“	Inches
°	Degrees
Ave	Average
BOD_5	Five Day Biochemical Oxygen Demand
CDNSWC	Carderock Division, Naval Surface Warfare Center
CHT	Collection Holding and Transfer System
cfm	cubic feet per minute
cfu	Colony Forming Units
EDM	Engineering Developmental Model
FC	Fecal Coliform
ft^2	Square feet
ft/s	Feet per second
gal/min	Gallon per minute
GUI	Graphical User Interface
GRP	Glass Reinforced Plastic
GW	Graywater
Hp	Horse power
HRT	Hydraulic retention time
LMH	Liters per square meter per hour
mg/L	Milligrams per liter
MPN	“Most Probable Number”: an analytical method for counting bacterial colonies
MWCO	Molecular Weight Cut-off
n/a	Not applicable
NAVSEA	Naval Sea Systems Command
Perm	Permeate
PLC	Programmable Logic Controller
PVC	Polyvinyl Chloride
psi	Pounds per square inch
PTFE	Polytetrafluoroethylene
Q_{20}	Permeability [normalized to 1 bar and 20^oC]
Temp	Temperature
THP	Transheader Pressure
TMP	Transmembrane Pressure
TSS	Total Suspended Solids
UF	Ultrafiltration
UNDS	Uniform National Discharge Standards
US EPA	United States Environmental Protection Agency
UV	Ultraviolet
VAC	Volts Alternating Current

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Author Biography

John Benson received his BS degree in Mechanical Engineering and MS degree in Environmental Engineering from the University of Maryland. He is a registered Professional Engineer in the State of Maryland. He joined the Naval Surface Warfare Center, Carderock Division Environmental Quality Department in 1990 as a project engineer and is now managing the non-oily wastewater(graywater and blackwater) project area.

Mr. Ivan Caplan graduated from Drexel University (Philadelphia, Pennsylvania) with a BS in Metallurgical Engineering and was awarded a MS degree from the Johns Hopkins University (Baltimore, Maryland) in Mechanics and Materials Science. Mr. Caplan has spent most of his career at the Carderock Division, Naval Surface Warfare Center (NSWC) and is currently the Head of the Wastewater Management Branch in the Carderock Division's Environmental Quality Department. Previously, Mr. Caplan managed the US Navy's Applied Research Program in Ship & Submarine Materials Technology. In addition, Mr. Caplan was manager of the US Navy's Titanium Technology Program Office, and during his government career, held several external Program Manager positions, on at the Naval Sea Systems Command and another at the Air Force Office of Scientific Research.

Rachel Jacobs received BS degrees in Chemical Engineering and Marine Biology from the University of Maryland, College Park. After working for the Naval Research Laboratory in Washington, DC and the Center for Marine Biotechnology in Baltimore, MD she joined the staff of the Naval Surface Warfare Center's Environmental Quality Department in 1997. Since that time, Ms. Jacobs has worked in the non-oily wastewater treatment area, and her principal responsibility has been to technically supervise the evaluation, operation, and modification of the laboratory tubular membrane ultrafiltration system for graywater treatment.

Table 1. Effluent Water Quality Performance Goals for Graywater Treatment (Minimum of MARPOL Annex IV & US Coast Guard MSD Type II Standards)

Water Quality Parameter	Effluent Water Quality Goal
Biochemical Oxygen Demand (BOD_5)	≤ 50 mg/L
Total Suspended Solids (TSS)	≤ 100 mg/L
Fecal Coliform (FC)	≤ 200 colony forming units / 100 ml

Table 2. Results of Laboratory Evaluation of In-Tank Membrane/Bioreactor System with Graywater

HRT (hours)	Average Flux at 20^0C (LMH)	Test Duration (hours)	Average BOD (mg/L)		Average TSS (mg/L)		Average Fecal Coliform (cfu/100 ml)	
			Feed	Permeate	Feed	Permeate .	Feed	Permeate
18	23	433	N/A	41	N/A	N/A	N/A	N/A
6	17	880	342	10	197	2	2.7 x E5	42
6	12	764	506	6	238	10	6.4 x E4	16
3	9	662	1426*	93	1278	7	6.6 x E6	490
		Shipboard Graywater **	845	-	345		4.2 x E7	-

N/A - not available

* Carderock test with stronger graywater feed source

** USS L.Y. SPEAR